EXCLUSIVE PROCESSES INDUCED BY ANTIPROTONS

OPPORTUNITIES FOR QCD STUDIES

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"Relativistic Nuclear Physics & Quantum Chromodynamics"

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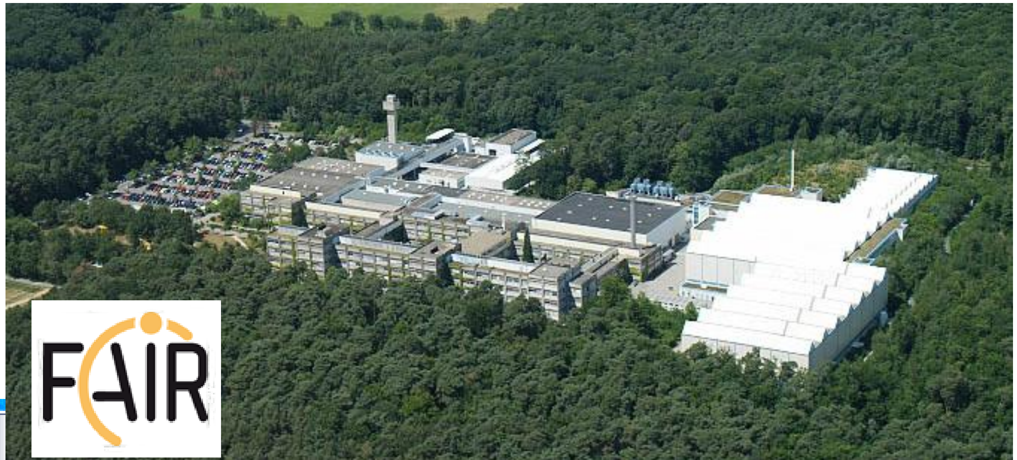
PLAN

- Introduction
  - Qcd tests :counting rules, helicity conservation
  - Contradicting results from experiments
- Examples : pbar-p annihilation
  - S-channel vector meson exchange
    - Annihilation into a lepton pair and a pion
  - Vacuum excitation
    - kaon to pion ratio
- Conclusions

Antiprotons at Panda, FAIR

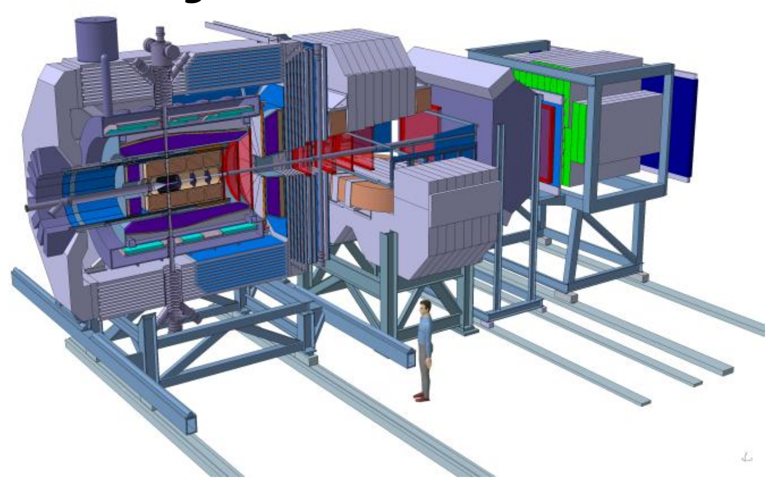


- *Highest rates*
- *Good E,p resolution*
- *Good Particle Identification*

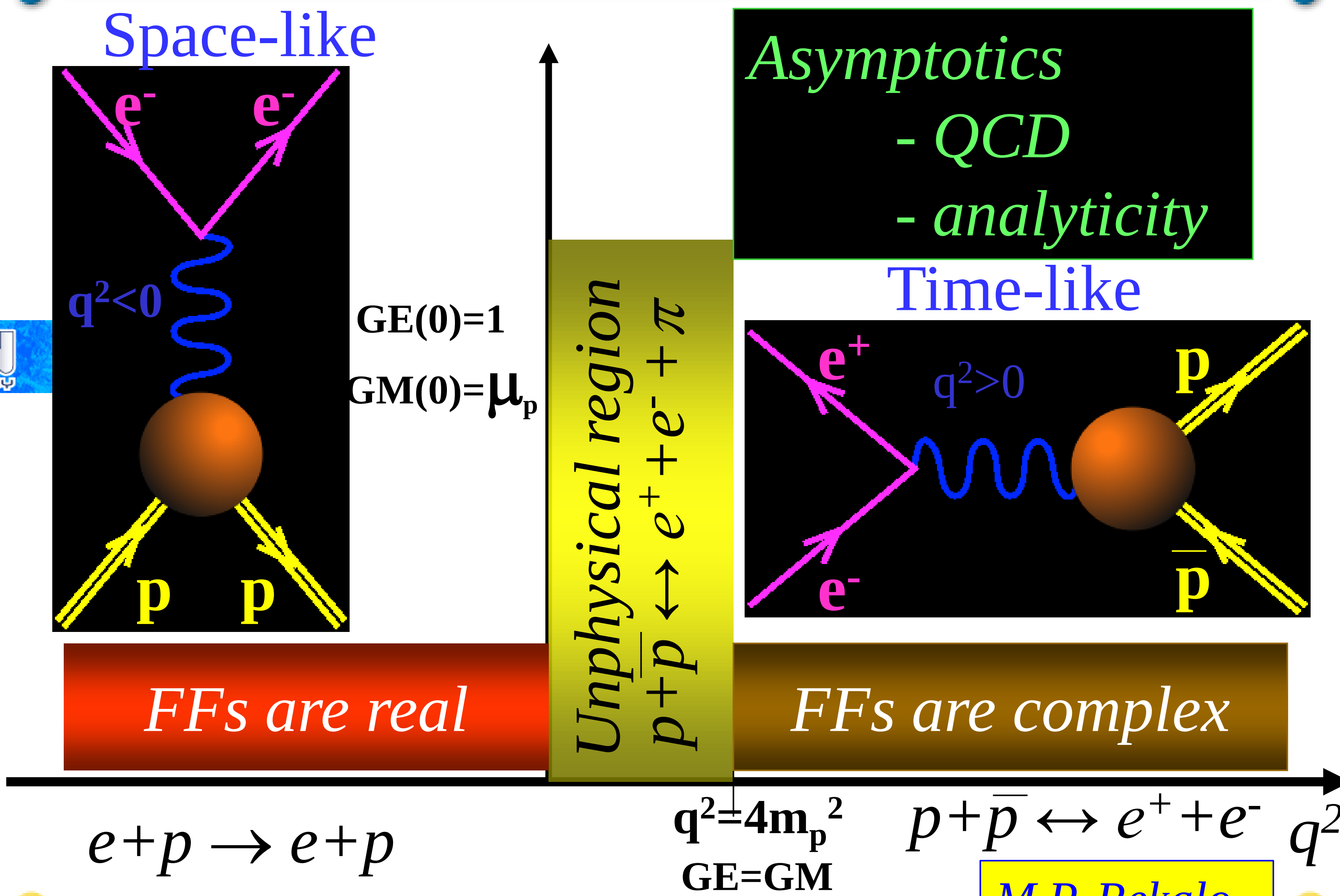
Antiprotons, produced by a primary proton beam will be filled into the High Energy Storage Ring (HESR) and will collide with a fixed target in the PANDA detector.

Parameters

- *Injection of p at 3.7 GeV*
- *Slow synchrotron (1.5-14.5 GeV/c)*
- *Storage ring for internal target*
- *Luminosity up to L~ $2x10^{32}$ cm-2s-1*
- *Beam cooling (stochastic & electron*

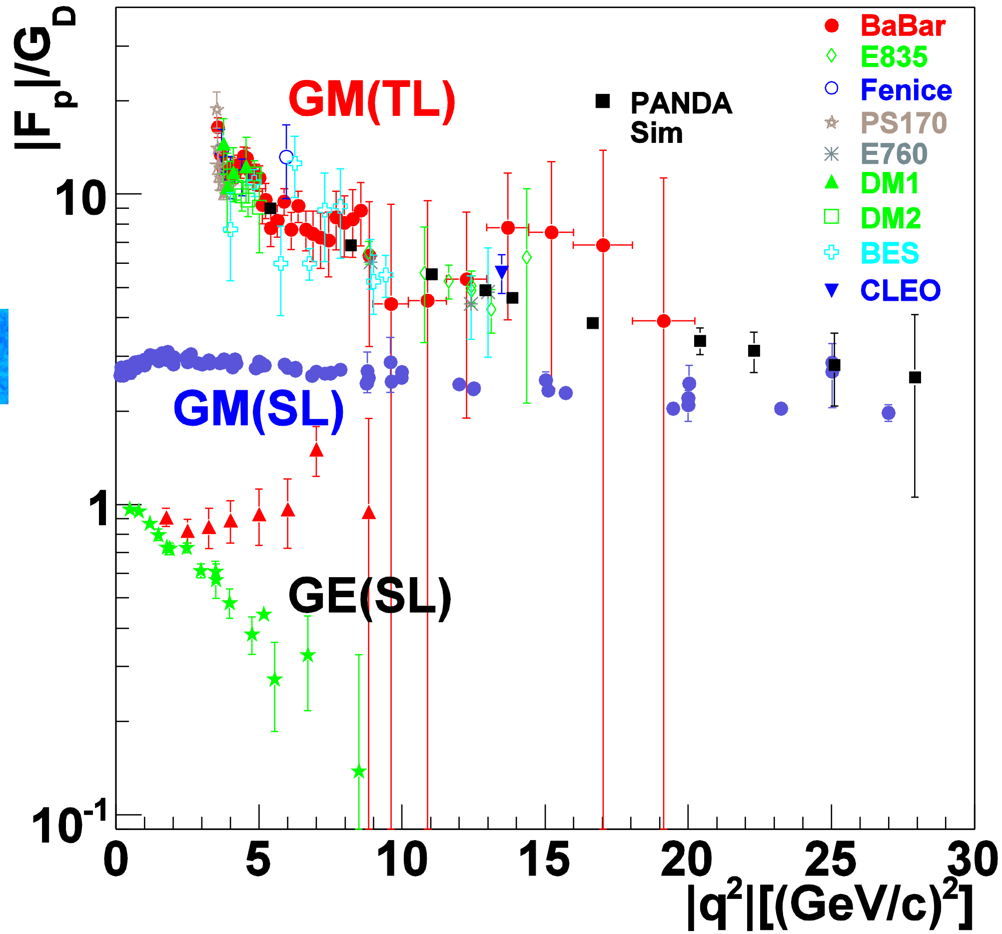


Analyticity



M.P. Rekalo

Phragmèn-Lindelöf theorem

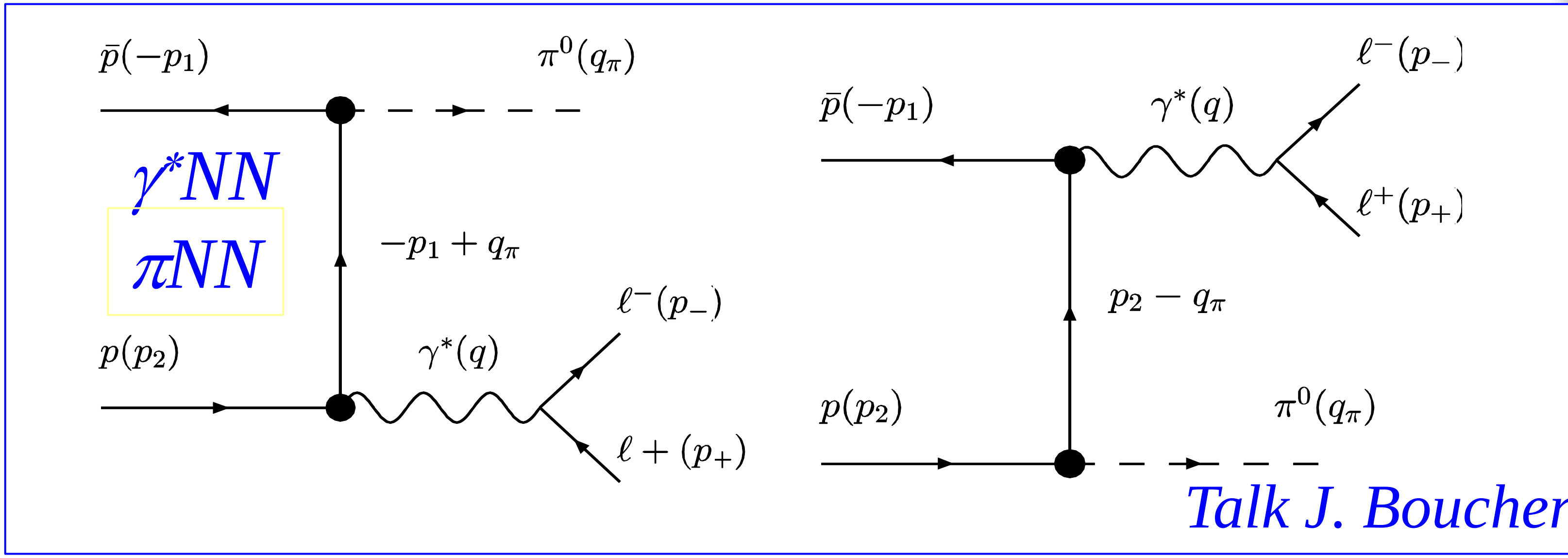


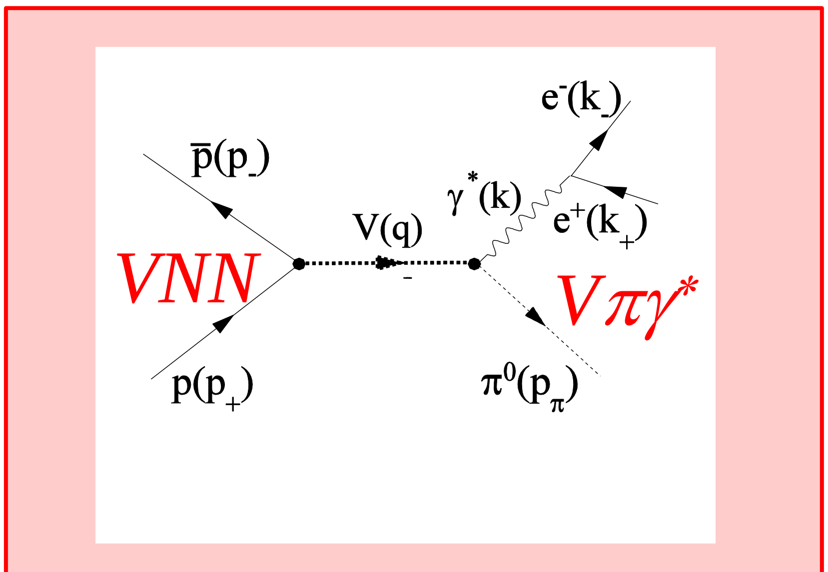
Connection with QCD asymptotics?

Applies to NN and $\overline{N}N$ Interaction
(Pomeranchuk theorem)
t=0 : not a QCD regime!

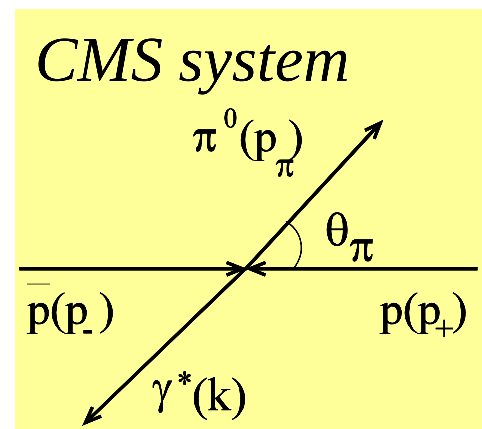
E. T-G. and M. P. Rekalo, Phys. Lett. B 504, 291 (2001)
E. T-G. e-Print: ***arXiv:0907.4442*** *[nucl-th]*

The reaction $p + \bar{p} \to e^+ + e^- + \pi^0$



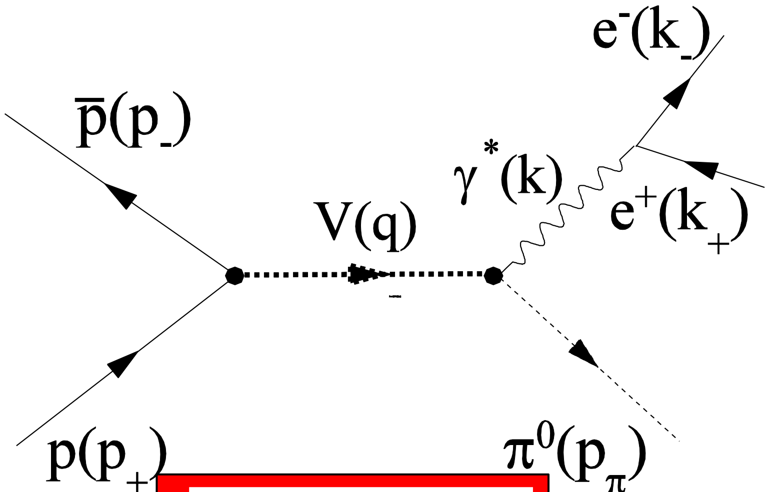


$V = \rho, \omega, \phi, J/\Psi, ..$

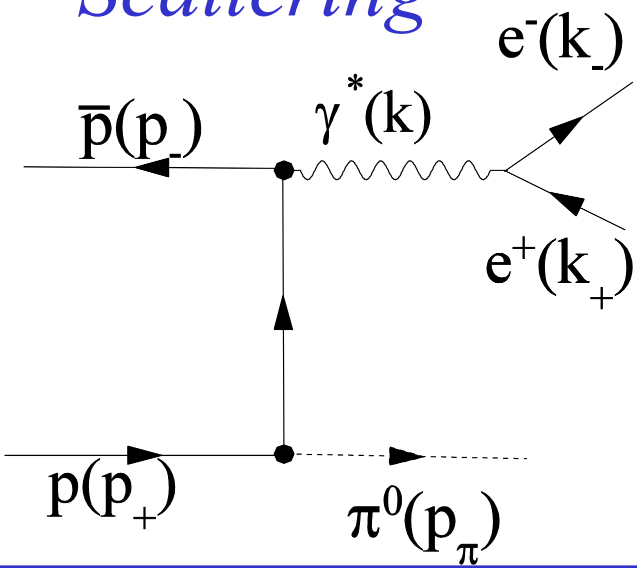


The reaction $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

"Annihilation"



"Scattering"



$$d\sigma_a \propto 1/s$$

$$d\sigma_s \propto \frac{1}{q^2}\left(\frac{s}{M^2}\right)^{2[\alpha_p(q^2)-1]}$$

At large scattering angles $\quad q^2 \sim s$

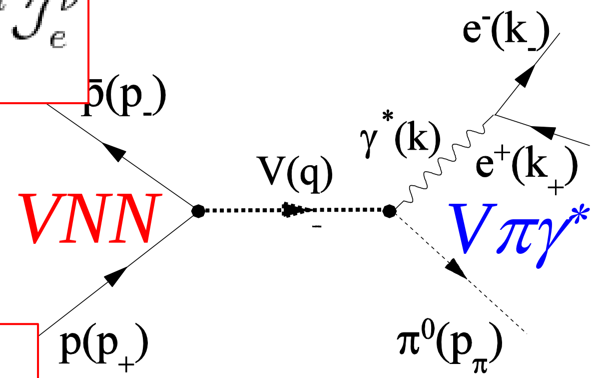
Regge trajectory of the proton

$$\frac{d\sigma_s}{d\sigma_a} \propto \left(\frac{s}{M^2}\right)^{2[\alpha_p(q^2)-1]} \ll 1$$

$$\alpha_p(q^2) < 1/2 \quad q^2 < 0$$

Cross section for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

$$\mathcal{M} = 4\pi\alpha \frac{G_{V\pi\gamma^*}}{e} \frac{\epsilon_{\mu\nu\rho\sigma} q^\rho k^\sigma}{k^2 \left(q^2 - M_V^2 + i M_V \Gamma_V\right)} \mathcal{J}_p^\mu \mathcal{J}_e^\nu$$



$$\mathcal{J}_e^\nu = \bar{u}(k_-)\gamma^\nu v(k_+)$$

$$\begin{aligned} \mathcal{J}_p^\mu &= \bar{v}(p_-)\Gamma_V^\mu u(p_+), \\ \Gamma_V^\mu &= F_1^V\left(q^2\right)\gamma^\mu + \frac{\sigma^{\mu\nu} q_\nu}{2M} F_2^V\left(q^2\right) = \\ &= \left[F_1^V\left(q^2\right) + F_2^V\left(q^2\right)\right]\gamma^\mu + \frac{\Delta^\mu}{2M} F_2^V\left(q^2\right) \end{aligned}$$

VNN: Parametrization and constants from Bonn potential

$$F_1^V(s) = \frac{\Lambda_V^2 - M_V^2}{\Lambda_V^2 + s}, \qquad F_2^V(s) = \kappa_V F_1^V(s)$$

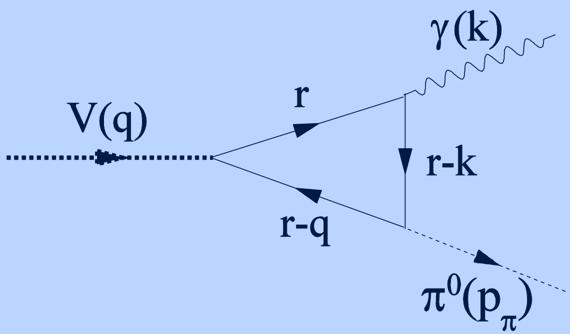
R.Machleidt, Phys. Rev. C63, 024001 (2001)

The vertex $V\pi\gamma*$

$$G_{V\pi\gamma^*}\left(q^2\right)\epsilon_{\mu\nu\sigma\rho}k^\sigma q^\rho,$$

Irfu cea saclay

NJL model



$$G_{V\pi\gamma^*}\left(q^2\right) = \frac{e g_{Vqq} I_\Delta\left(q^2\right)}{8\pi^2 F_\pi},$$

Phenomenology

Monopole
Dipole

$$G_{V\pi\gamma^*}\left(q^2\right) = \frac{g_{V\pi\gamma}\left(0\right)}{1+q^2/m_V^2}$$

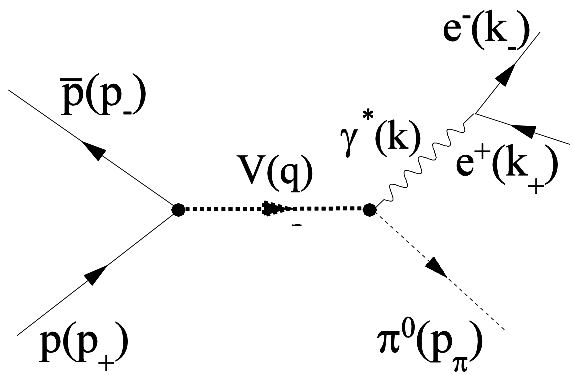
Radiative decay $V\rightarrow\pi\gamma*$

$$\Gamma\left(V\to\pi\gamma\right) = \frac{M_V\alpha}{24}|g_{V\pi\gamma}(0)|^2\left(1-\frac{M_\pi^2}{M_V^2}\right)^3$$

Cross section for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

The cross section:

$$d\sigma = \frac{1}{4I} \int \sum_{spin} |\mathcal{M}|^2 \, d\Phi_3$$



The incident flux:

$$I = \sqrt{(p_+ p_-)^2 - M^4} = (1/2)\sqrt{s\,(s - 4M^2)}$$

The three particle phase space:

$$d\Phi_3 = (2\pi)^4 \, \delta^4 \left(p_+ + p_- - k_+ - k_- - p_\pi\right) \frac{d^3\vec{k}_+}{(2\pi)^3 \, 2E_+} \frac{d^3\vec{k}_-}{(2\pi)^3 \, 2E_-} \frac{d^3\vec{p}_\pi}{(2\pi)^3 \, 2E_\pi},$$

Cross section for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

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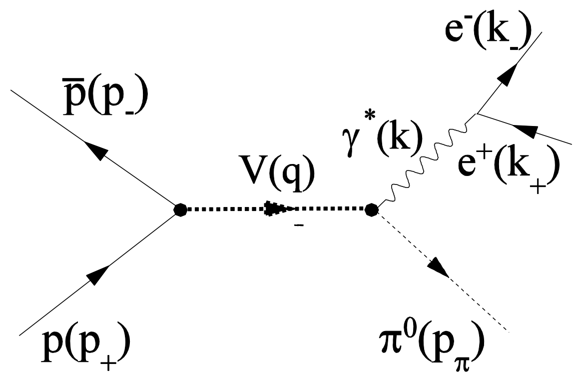
Generalization to $\omega+\rho$ mesons

$$|\mathcal{M}_V|^2 \rightarrow \left|\mathcal{M}_\omega + \mathcal{M}_\rho e^{i\phi}\right|^2$$



- F_2 structure
- relative phase $\phi = 101^o$

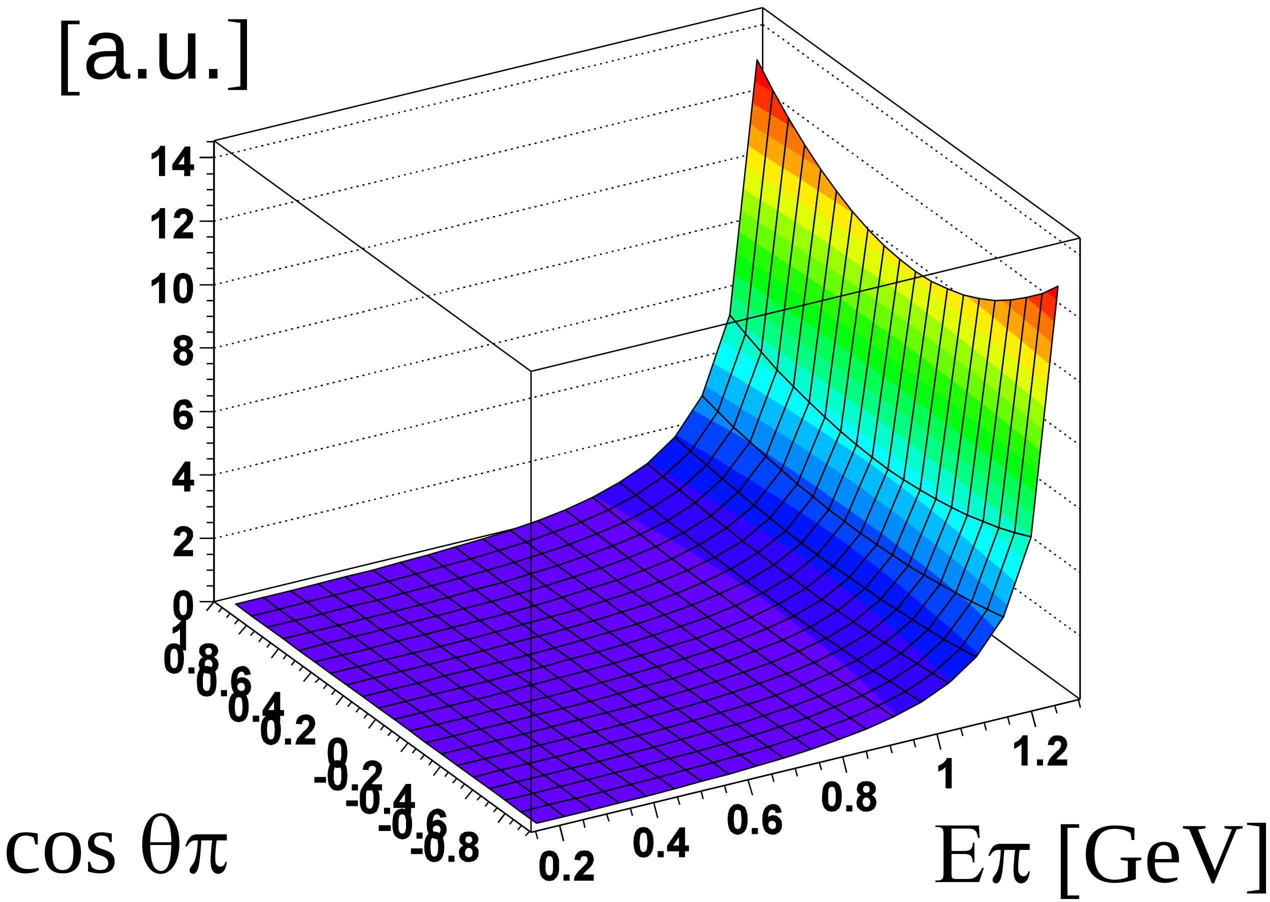
$$\sigma_0 = \frac{G^2_{\omega\pi\gamma^*}(s)\,\alpha\,|F_1^\omega(s)|^2\,s^2}{2^6\pi^3 3\beta\ \left[\left(s-M_\omega^2\right)^2 + M_\omega^2\Gamma_\omega^2\right]}$$

$$\sigma_0 \rightarrow \tilde{\sigma}_0 = \frac{\alpha s^2}{2^3\pi^3 3\beta}\left|\frac{g_{\omega\pi\gamma^*}\,|F_1^\omega(s)|}{s-M_\omega^2+iM_\omega\Gamma_\omega} + \frac{g_{\rho\pi\gamma^*}\,|F_1^\rho(s)+F_2^\rho(s)|}{s-M_\rho^2+iM_\rho^2\Gamma_\rho^2}e^{i\phi_\rho}\right|^2$$

Heath Bland O'Connell, et al,, Prog. Part. Nucl. Phys. 39, 201 (1997).

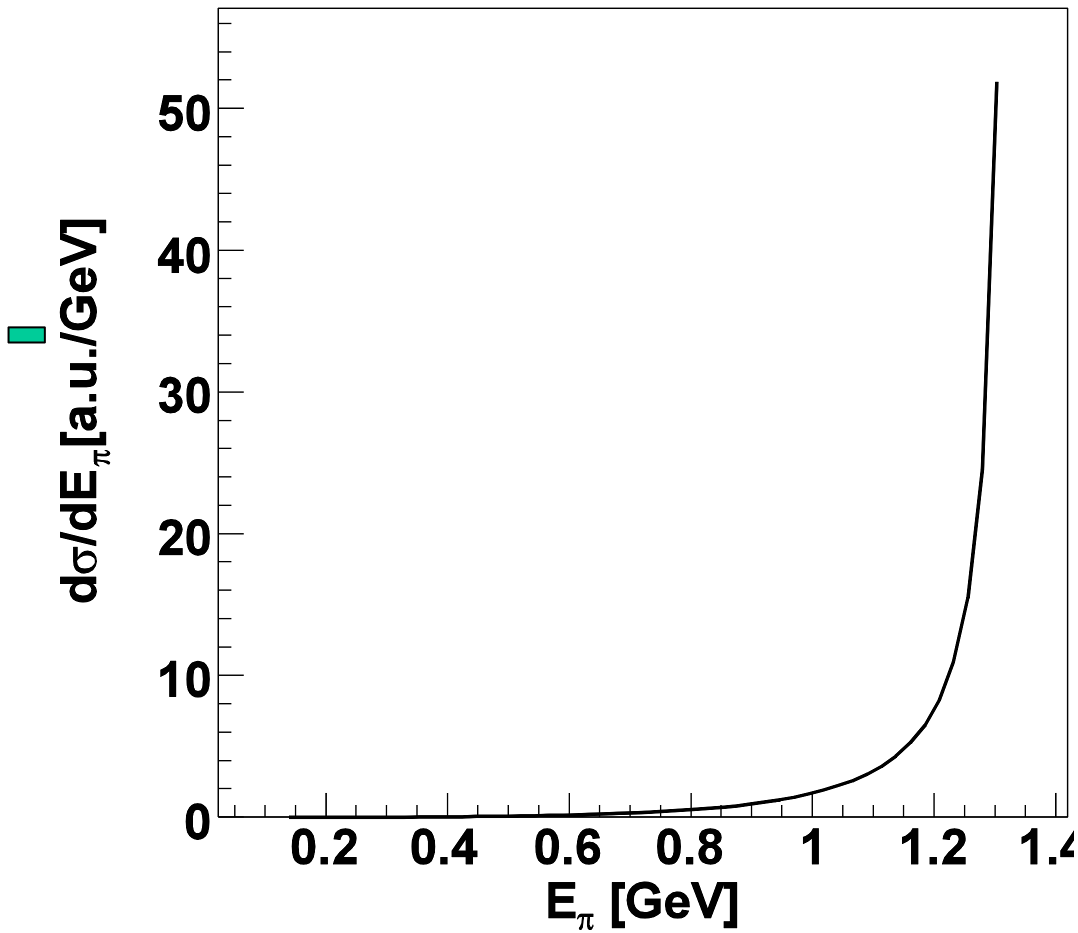
Cross section for $p + \bar{p} \to e^+ + e^- + \pi^0$

$$\frac{d^2\sigma}{dE_\pi dc_\pi} = \sigma_0 \frac{E_\pi^3\left(2-\beta^2\sin^2\theta_\pi\right)}{s\left(s+M_\pi^2-2E_\pi\sqrt{s}\right)},$$



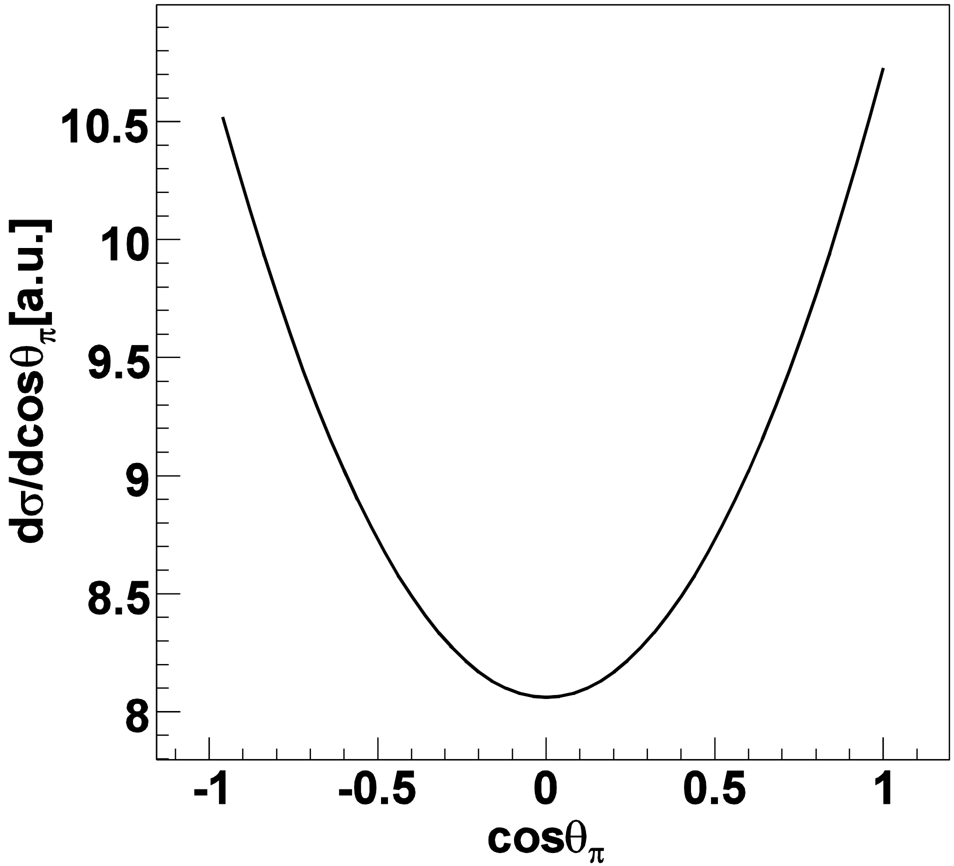
Cross section for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

$$\frac{d\sigma}{dE_\pi} = \int_{-1}^{1} dc_\pi \frac{d^2\sigma}{dE_\pi dc_\pi} = \sigma_0 \frac{4E_\pi^3}{s(s+M_\pi^2 - 2E_\pi\sqrt{s})}\left(1 - \frac{\beta^2}{3}\right)$$



Cross section for $p + \bar{p} \to e^+ + e^- + \pi^0$

$$\frac{d\sigma}{dc_\pi} = \int_{M_\pi}^{\frac{\sqrt{s}}{2}\left(1+\frac{M_\pi^2}{s}-\frac{4m_e^2}{s}\right)} dE_\pi \frac{d^2\sigma}{dE_\pi dc_\pi} = \frac{\sigma_0}{16}\left(2-\beta^2\sin^2\theta_\pi\right)\left(\ln\frac{s}{4m_e^2}-\frac{11}{6}\right)$$



Cross section for $\bar{p} + p \to \gamma + \pi^0$

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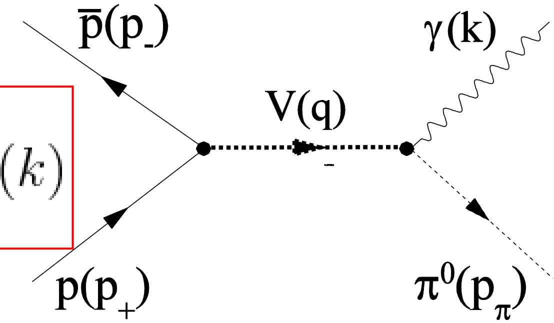
- *The matrix element:*



$$\mathcal{M}_V = 4\pi\alpha \frac{G_{V\pi\gamma} G_{Vpp}}{e} \frac{\epsilon_{\mu\nu\rho\sigma} q^\rho k^\sigma}{(q^2 - M_V^2 + i M_V \Gamma_V)} \mathcal{J}_p^\mu e^\nu(k)$$

- *The total cross section:*

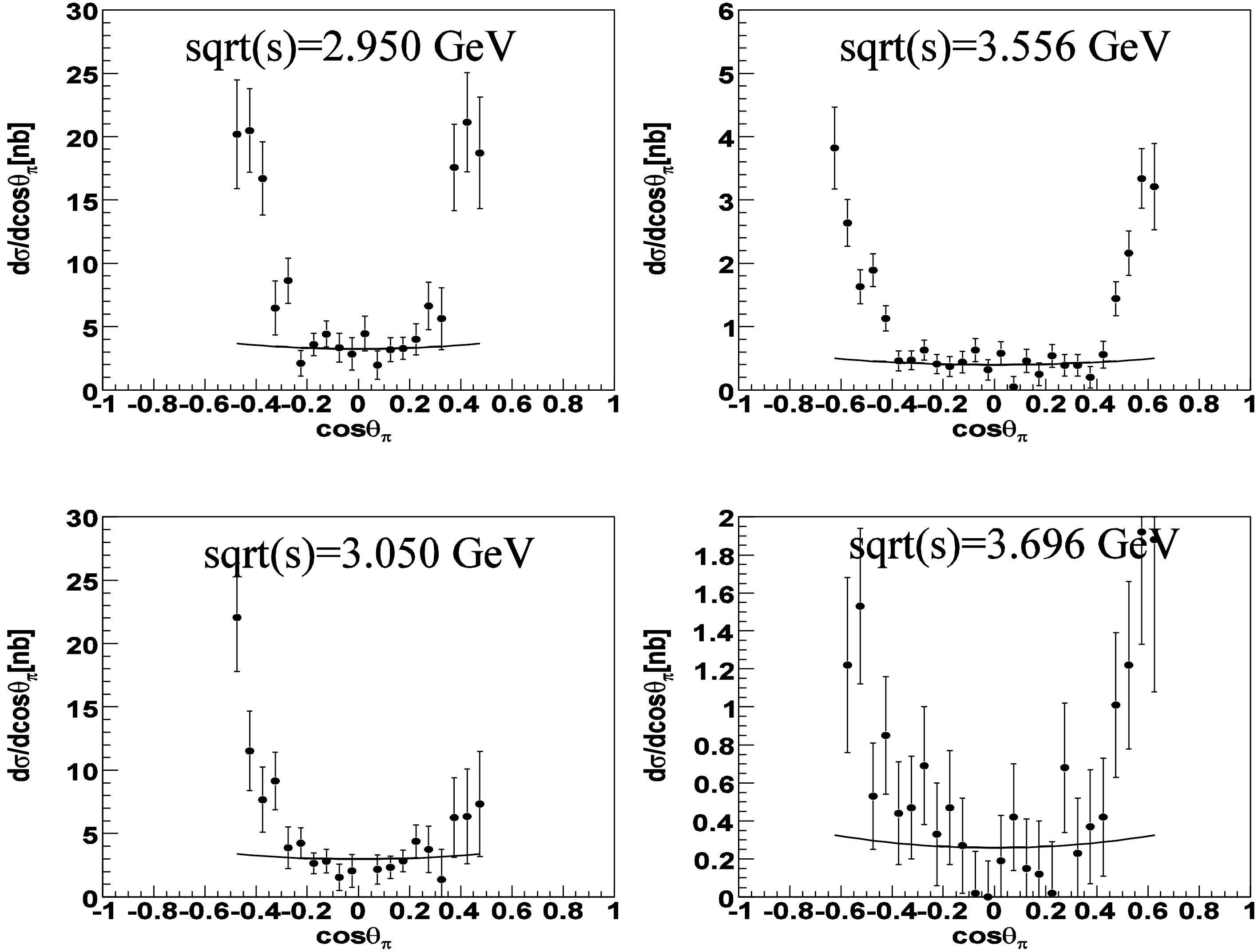
$$\sigma(s) = \frac{G_{V\pi\gamma}^2 G_{Vpp}^2}{q^2 - M_V^2 \Gamma_V^2} \frac{(s - M_\pi^2)^3}{2^7 \pi} \left[4|F_1|^2 \left(\frac{1}{3} + \frac{M^2}{s} \right) + |F_2|^2 \left(1 + \frac{s}{6M^2} \right) - 4 Re(F_1 F_2^*) \right]$$

- *The differential cross section*

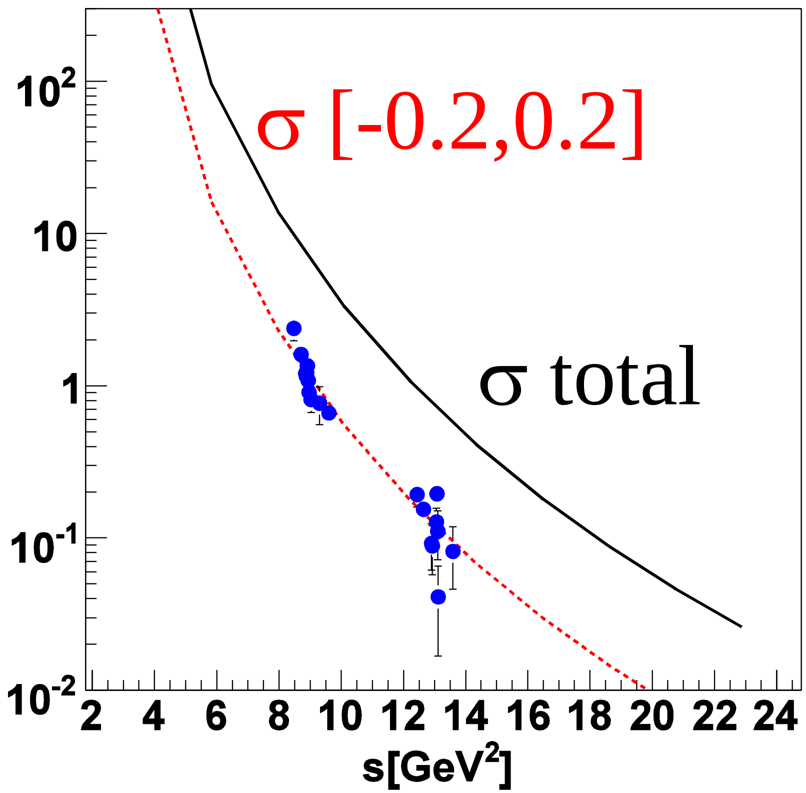
$$\frac{d\sigma}{d\Omega}(s) = \frac{G_{V\pi\gamma}^2 G_{Vpp}^2}{q^2 - M_V^2 \Gamma_V^2} \frac{(s - M_\pi^2)^3}{2^9 \pi^2} \left\{ |F_1|^2 \left(1 + \cos^2\theta_\gamma + \frac{4M^2}{s} \right) + |F_2|^2 \left[\frac{s}{4M^2} (1 - \cos^2\theta_\gamma) + 1 \right] - 4 Re(F_1 F_2^*) \right\}$$

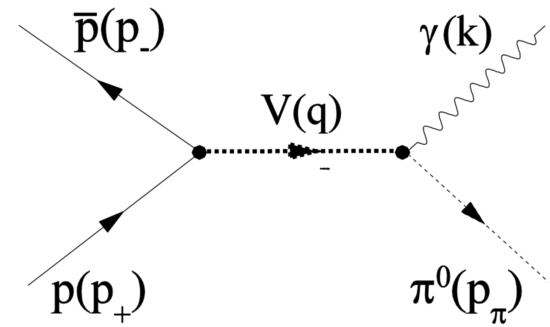
Cross section for $\bar{p} + p \rightarrow \gamma + \pi^0$

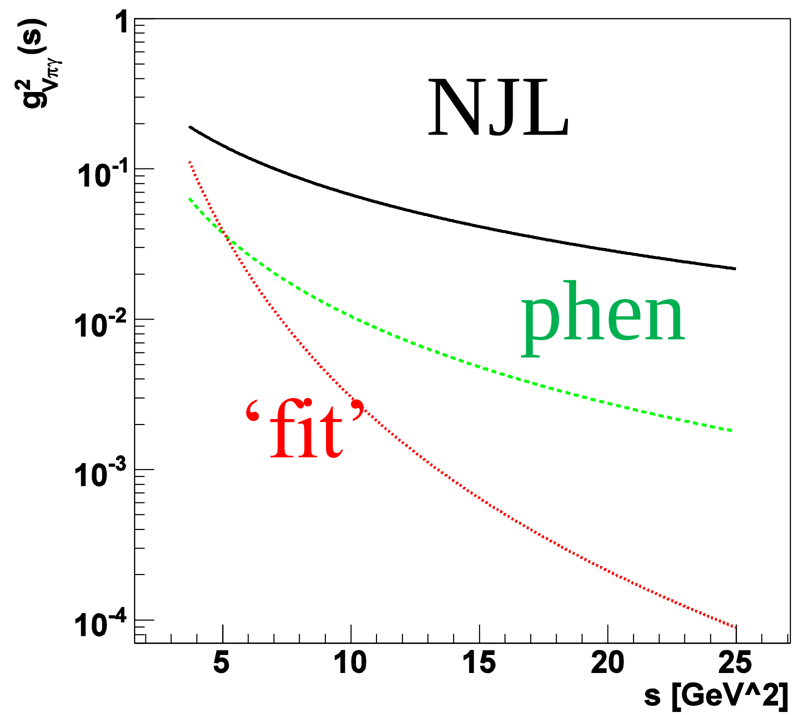
T.A. Armstrong et al, PRD, 56 (1997) 2509



Total cross section for $\bar{p} + p \to \gamma + \pi^0$







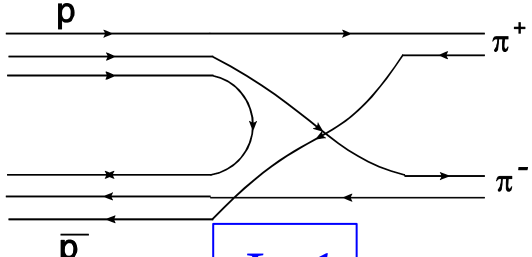
Vacuum excitations

Hadronic ratios in $p\bar{p}$ annihilation

$p\bar{p}$ bound state: $^{2S+1}L_J$, $J=L+S$

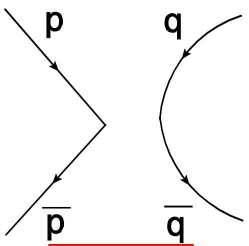
$L=0$: $^1S_0$, $^3S_1$ $L=1$: $^3P_0$, $^3P_1$, ...

Threshold region: only S state



$J=1$

Quark rearrangement



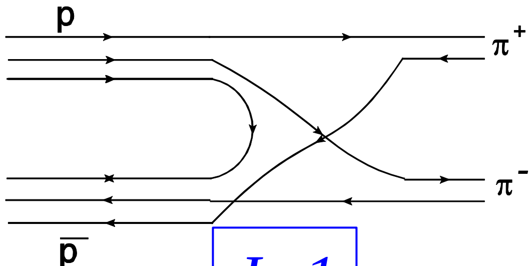
$J=0$

Excited vacuum

*Main decay:from **the triplet state** to a charged pion pair*

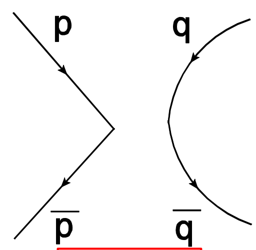
No intrinsic strangeness in the proton!

Hadronic ratios in $p\bar{p}$ annihilation



J=1

Quark rearrangement



J=0

Excited vacuum

Our suggestion:

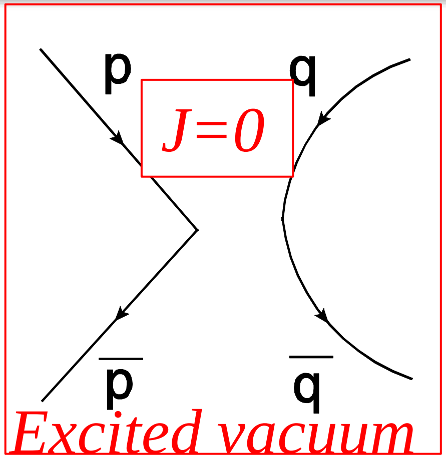
$$R_s = \frac{(p\bar{p})_{\mathcal{J}=0} \to K\bar{K}}{(p\bar{p})_{\mathcal{J}=0} \to \pi^+\pi^-}, \quad R_p = \frac{(p\bar{p})_{\mathcal{J}=1} \to K\bar{K}}{(p\bar{p})_{\mathcal{J}=1} \to \pi^+\pi^-}$$

Our prediction:

Threshold region (L=0): $R_p \ll R_S \simeq 1$

E.A. Kuraev, E.T-G, PRD 81,017501 (2010)

Exclusive processes: hadronic ratios



E.A. Kuraev, E.T-G, PRD 81,017501 (2010)

$$\beta_q = \sqrt{1 - m_q^2/E_q^2}, \quad E_u = E_s = m_p,$$

$$m_u = m_d = 280 \text{ MeV}$$

$$m_s = 400 \text{ MeV}$$

$$M \sim \bar{u}(p_-)v(p_+)$$

$$|M(\bar{p}p \to EV \to \bar{q}q)|^2 \sim Tr(\hat{p}_+ - m_q)(\hat{p}_- + m_q) = 8\beta_q^2 m_p^2, \; q = u, d, s,$$

- *Correct for phase space* $\phi_\pi/\phi_K = \beta_\pi/\beta_K$

$$\frac{Y_{KK}}{Y_{\pi\pi}} = \frac{1/2}{3+1/2}\frac{\beta_K}{\beta_\pi}\left(\frac{\beta_s}{\beta_u}\right)^2 = 0.108$$

- *Produced with equal probability in all spin states: (supported by statistical arguments)*

16 June 1994

ELSEVIER

PHYSICS LETTERS B

Physics Letters B 329 (1994) 407–412

The Asterix collaboration

Measurement of the $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ annihilation frequencies in a 5 mb hydrogen gas target

V.G. Ableev [i], A. Adamo [a], M. Agnello [b], A. Andrighetto [ℓ], F. Balestra [g], G. Belli [c],

Table 2
Annihilation frequencies and efficiencies for $\pi^+\pi^-$ and K^+K^-

n	N_π	N_K	BG_π	BG_K	ϵ_π	ϵ_K	f_π	f_K
1.37 ± 0.04	4318 ± 66	405 ± 20	< 6	49 ± 11	0.074 ± 0.002	0.057 ± 0.002	4.26 ± 0.11	0.46 ± 0.03

n is the number of annihilations in the H_2 target (in 10^7); N_π is the number of $\pi^+\pi^-$ events after kinematical fit selection; N_K is the number of K^+K^- events after kinematical fit selection; BG_π is the number of $\pi^+\pi^-\pi^0$ background events evaluated from Monte Carlo in the $\pi^+\pi^-$ data sample; BG_K is the number of $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$ background events recognized by TOF in the K^+K^- data sample; ϵ_π is the detection and reconstruction efficiency for $\pi^+\pi^-$; ϵ_K is the detection and reconstruction efficiency for K^+K^-; f_π is the annihilation frequency (in 10^{-3}) for $\pi^+\pi^-$; f_K is the annihilation frequency (in 10^{-3}) for K^+K^-. Systematic and statistical errors are added quadratically.

$$R = f(K^+K^-)/f(\pi^+\pi^-) = 0.108 \pm 0.007.$$

Kinematics at Panda-FAIR

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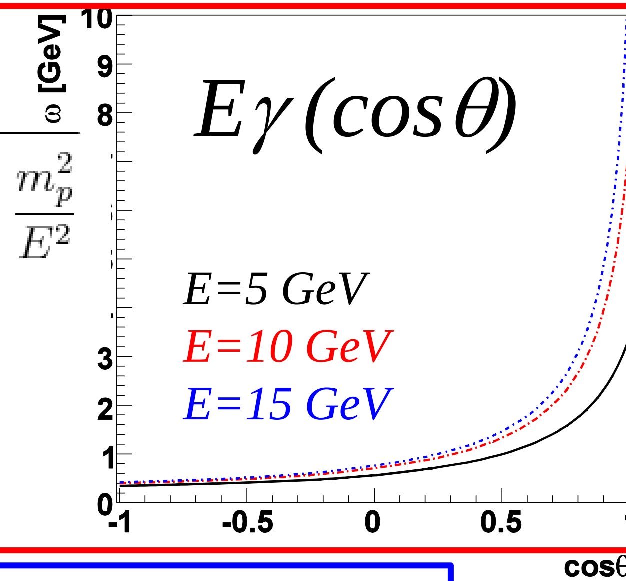
The beam momentum in the range 1.7-15 GeV/c.
The lowest total energy squared is s=5.4 GeV^2
How to reach the threshold region s=(2m$_p$) ^{2}=3.6 GeV ^{2} ?

→ *Real or virtual photon emission*

$$\bar{p}(p_1) + p(p_2) \to \gamma(k) + B(P),$$

$$k^2 = 0,\ P^2 = 4m_p^2,\ p_1^2 = p_2^2 = m_p^2;\ \beta = \sqrt{1 - \frac{m_p^2}{E^2}}$$

$$(p_1 + p_2 - k)^2 = 4m_p^2,\ \omega = \frac{E - m_p}{1 + \frac{E}{m_p}(1 - \beta\cos\theta)}$$



$$\bar{p}(p_1) + p(p_2) \to \gamma(k) + B(P),\ k^2 = M_X^2 \gg 0$$

$$E - \omega + \frac{M_X^2}{2m_p} - E(\omega - k\beta\cos\theta) \simeq m_p,\ \omega = k_0,\ k = \sqrt{\omega^2 - M_X^2}$$

E.A. Kuraev, E.T-G, PRD 81,017501 (2010)

Conclusions

- Antiproton-proton annihilation with high luminosity at Panda/FAIR will allow the study of exclusive processes.

  Determination of time-like form factors up to large q2

  Test of validity of pQCD and analiticity.

  Polarization observables?

- *the reactions* $\bar{p} + p \to e^+ + e^- + \pi^0$ *and* $\bar{p} + p \to \gamma + \pi^0$
  - *Determination of electromagnetic and axial nucleon FFs in the unphysical region;*
  - Determination of vector meson properties through S-channel vector meson exchange
- Pion/kaon pair production; vacuum excitations?
- *basic program with anti-proton beams:*

  Panda Physics Performance Report

  e-Print: **arXiv:0903.3905** [hep-ex]


Thank you for attention
Благодарю вас за внимание

The threshold region

- The probability to create a protonium state by slow moving antiproton is finite in the limit of zero velocity, due to the bound state factor:

$$|\Psi(0)|^2 = \frac{\chi}{1-e^{-\chi}}, \quad \chi = \frac{2\pi\alpha}{\beta},$$

which compensates the small phase volume

- Suppression factor for $^1S_0$ state (Boltzman probability):

$$W \sim exp(-2M/k_B T_d)$$

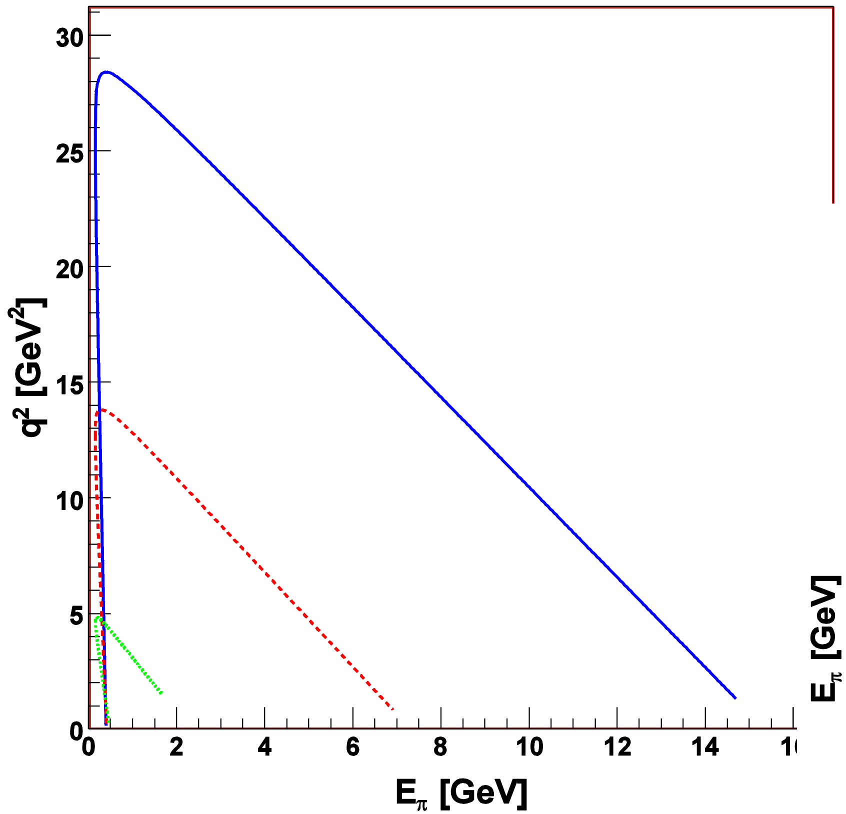
$$2M = 700 \text{ MeV}$$

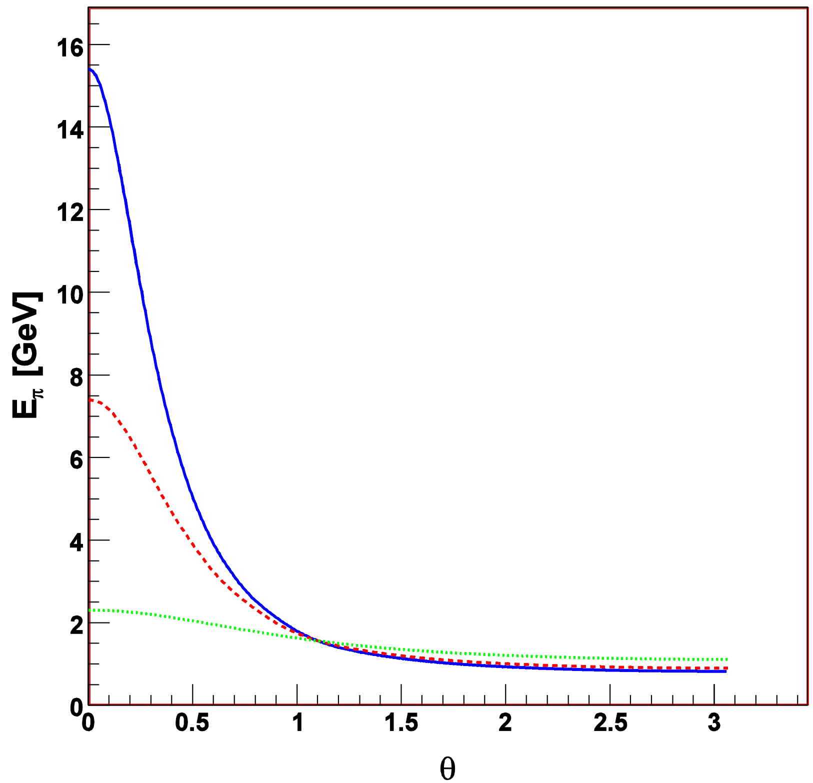
$$k_B T_d = 100 \text{ MeV};$$ deconfinement temperature

$$W \sim 10^{-3}$$

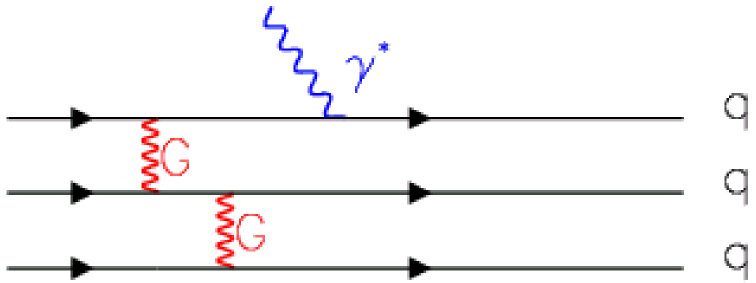
→ equal weight of singlet and triplet states

The kinematics for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$





Dipole Approximation and pQCD



Dimensional scaling

- $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks
- Setting $\beta^2 = (0.471 \pm .010)\ \mathrm{GeV}^2$ *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \mathrm{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \mathrm{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\ \mathrm{GeV}^2)^5]$

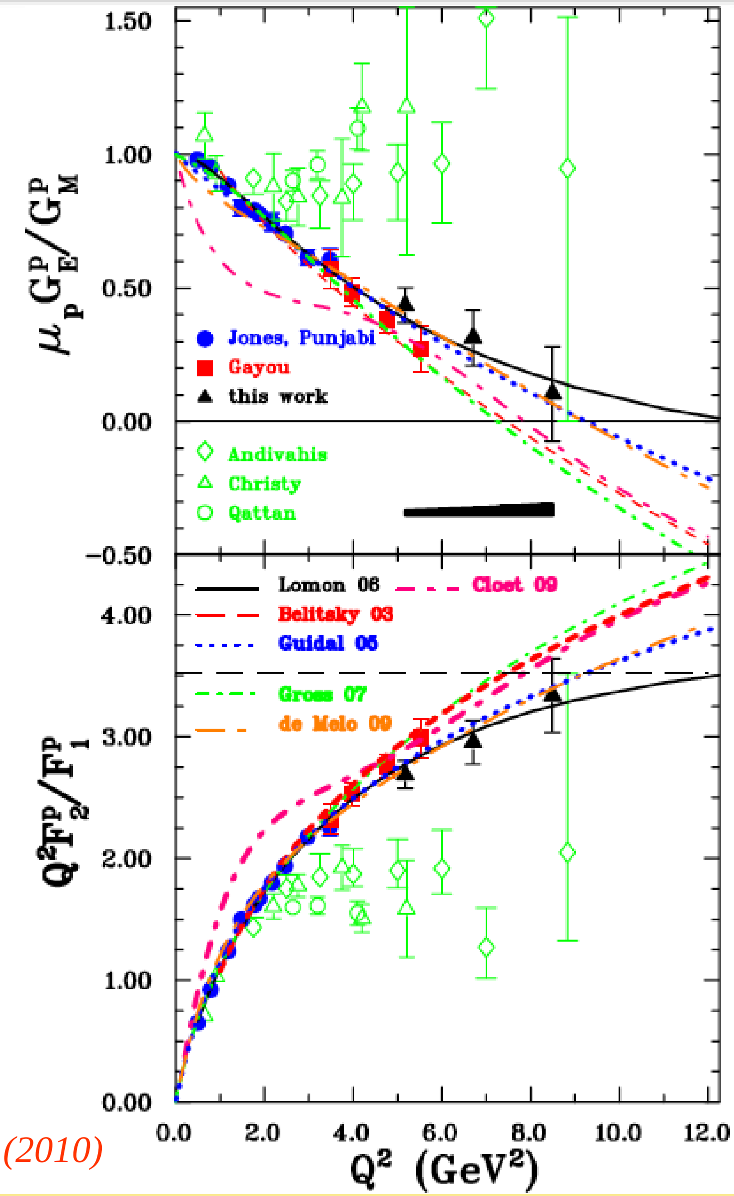
V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

Polarization experiments - Jlab

A.I. Akhiezer and M.P. Rekalo, 1967

GEp collaboration

1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn
2) linear deviation from the dipole function for the electric proton FF Gep
3) QCD scaling not reached
3) Zero crossing of Gep?
4) ***contradiction between polarized and unpolarized measurements***



A.J.R. Puckett et al, PRL (2010)

Phragmèn-Lindelöf theorem

Asymptotic properties for analytical functions

If f(z) →a as z→∞
along a straight line,
and f(z) →b as z→∞
along another straight line,
and f(z) is regular and bounded
in the angle between,
then a=b and f(z) →a uniformly in the angle.

$$\lim_{q^2\to-\infty} F^{(SL)}(q^2) = \lim_{q^2\to\infty} F^{(TL)}(q^2)$$

space − like: $(e^- + p \to e^- + p)$

time − like: $(e^+ + e^- \leftrightarrow \bar{p} + p)$

$$- F^{(TL)}(q^2) \to real, \text{ if } q^2 \to \infty$$

$$\mathcal{F} = |Im(F_2/F_1)|/|Re(F_2/F_1)| = \Delta$$

$$|P_y| = \Delta \quad \Delta=0.05,\ 0.1$$

$$\mathcal{R} = |F_2/F_1|_{TL}/|F_2/F_1|_{SL} = 1 + \Delta$$

E. T-G. and G. Gakh, Eur. Phys. J. A 26, 265 (2005)